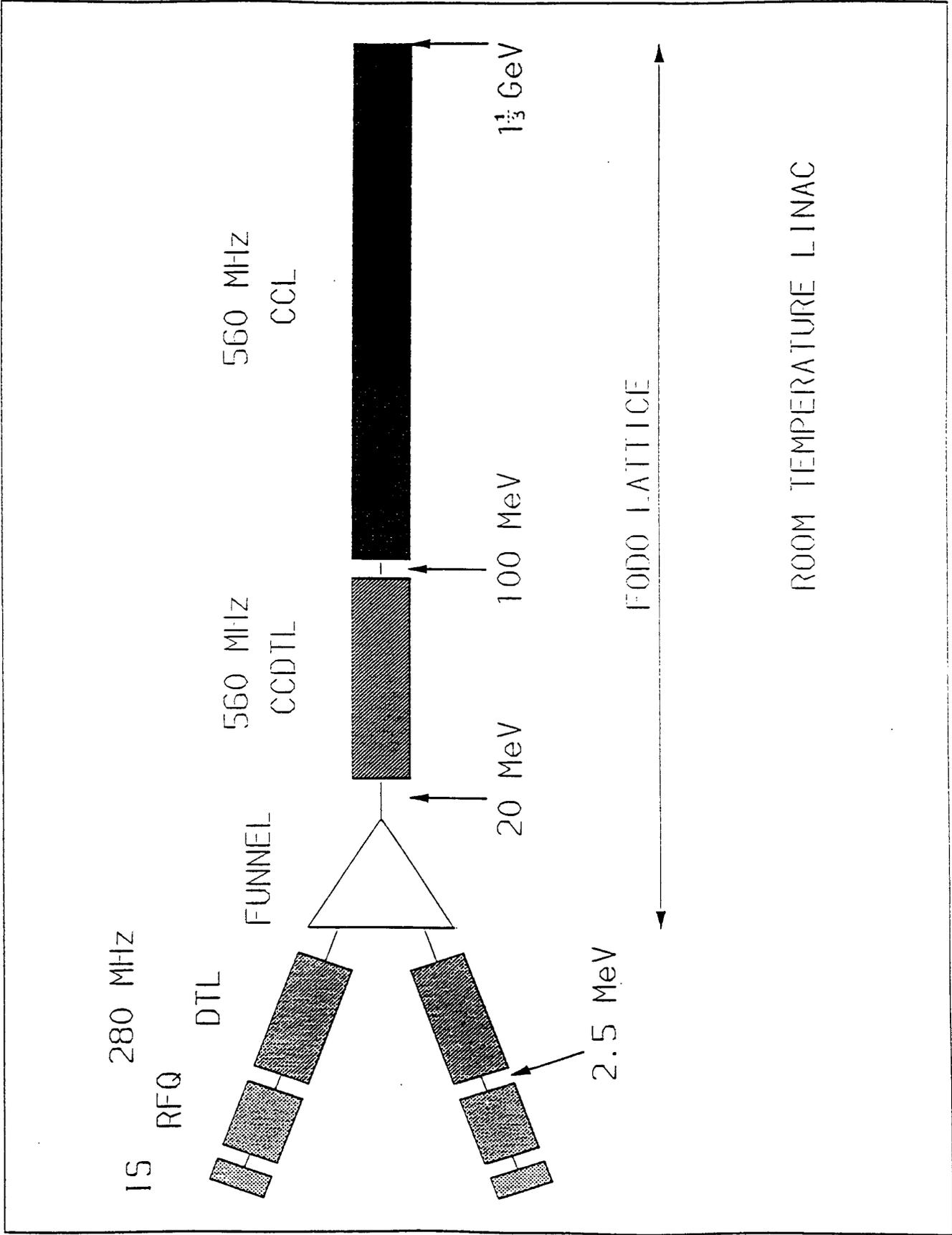


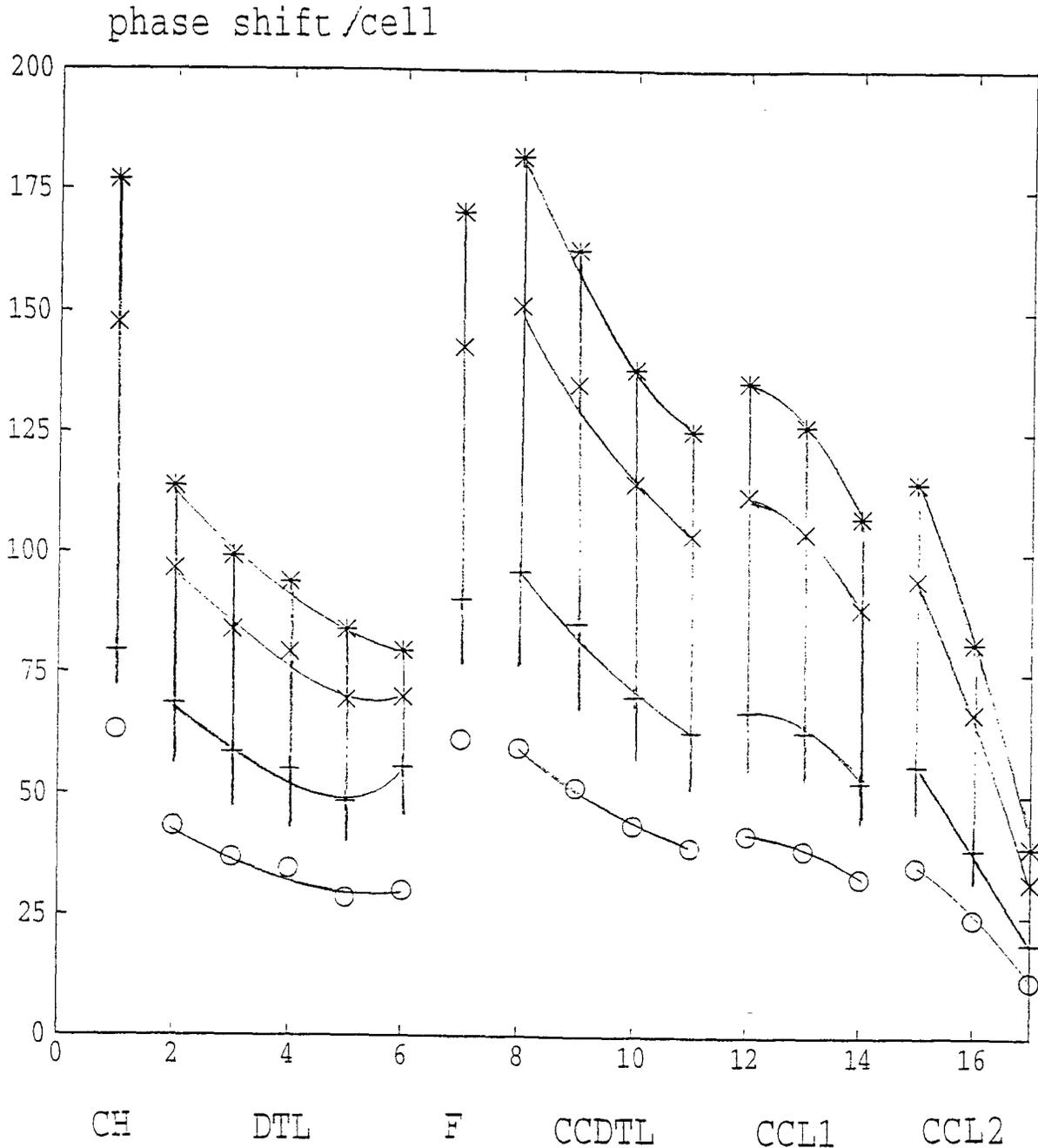
Instability Issues for ESS Linac and Rings

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LINAC COHERENT MODES



- low mode
- + quadrupole mode
- × high mode
- * zero current quadrupole mode

Coherent Mode Frequencies

1. Equal Transverse Tunes $\left(\sigma_{t_0} = \sigma_{x_0} = \sigma_{y_0} \right)$

$$\sigma_{env,Q} = 2\sigma_t \quad \sigma_{env,H}^2 = A + B \quad \sigma_{env,L}^2 = A - B$$

$$A = \sigma_{t_0}^2 + \sigma_t^2 + \frac{1}{2}\sigma_{l_0}^2 + \frac{3}{2}\sigma_l^2$$

$$B^2 = \left(\sigma_{t_0}^2 + \sigma_t^2 - \frac{1}{2}\sigma_{l_0}^2 - \frac{3}{2}\sigma_l^2 \right)^2 + 2(\sigma_{t_0}^2 - \sigma_t^2)(\sigma_{l_0}^2 - \sigma_l^2)$$

2. Unequal Transverse Tunes $\left(\sigma_{y_0} = \sigma_{x_0}(1+\alpha) \right) \quad (\alpha \lesssim 0.1)$

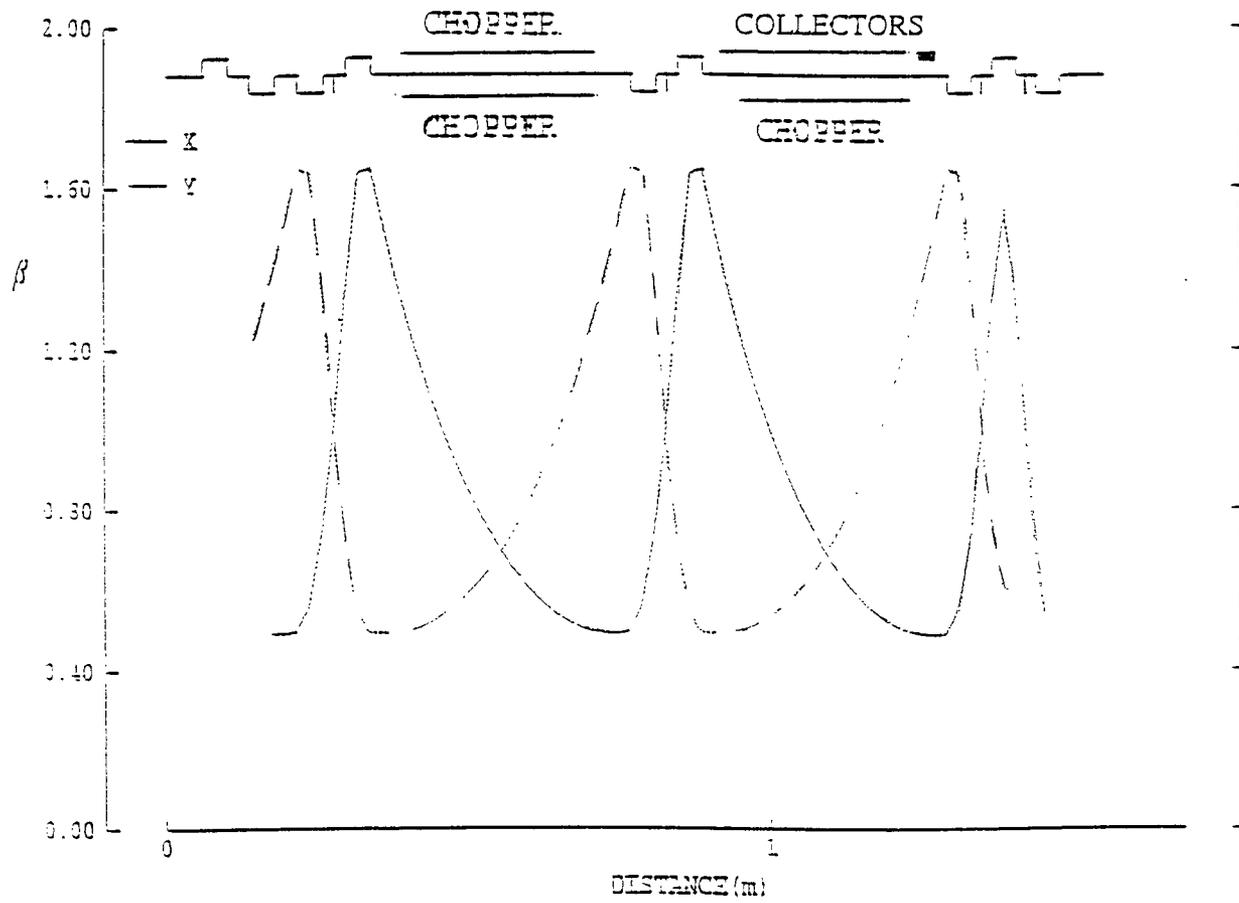
$$\sigma_{env,Q} = 2\sigma_x(1+\alpha)^{1/2m} \quad \sigma_{env,H}^2 = A_1 + B_1 \quad \sigma_{env,L}^2 = A_1 - B_1$$

$$A_1 = (1+\alpha)^{1/2m} \left(\sigma_{x_0}^2 + \sigma_x^2 \right) + \frac{1}{2}\sigma_{l_0}^2 + \frac{3}{2}\sigma_l^2$$

$$B_1^2 = \left((1+\alpha)^{1/2m} \left(\sigma_{x_0}^2 + \sigma_x^2 \right) - \frac{1}{2}\sigma_{l_0}^2 - \frac{3}{2}\sigma_l^2 \right)^2 + (1+\alpha)^{1/2m} 2(\sigma_{x_0}^2 - \sigma_x^2)(\sigma_{l_0}^2 - \sigma_l^2)$$

m = 1 for equipartitioning

m = 2 for equal transverse emittances



Chopper Beam Transport Line

Non-Linear Space Charge Forces

Ratio of non-linear to linear forces varies with aspect ratio a/b.

Example: 2-D Parabolic Transverse Density Distribution.

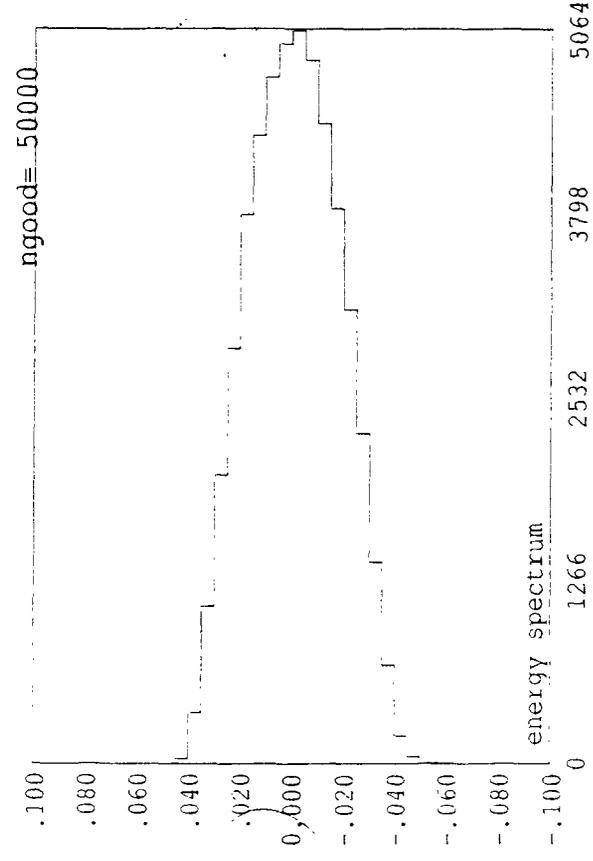
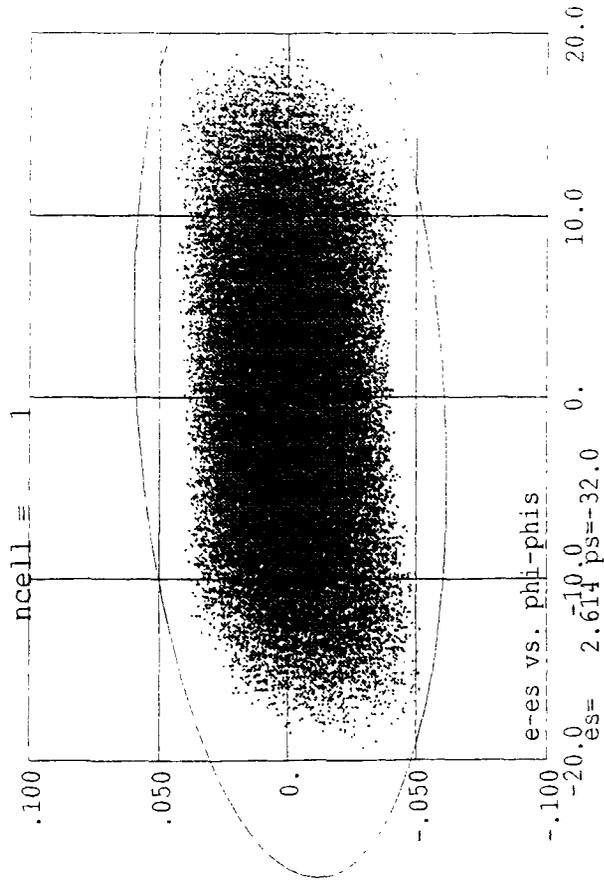
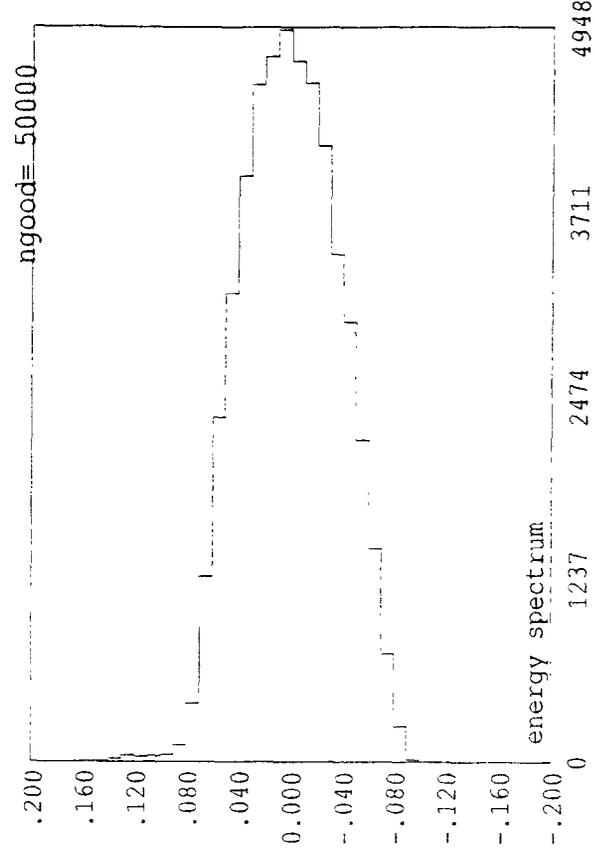
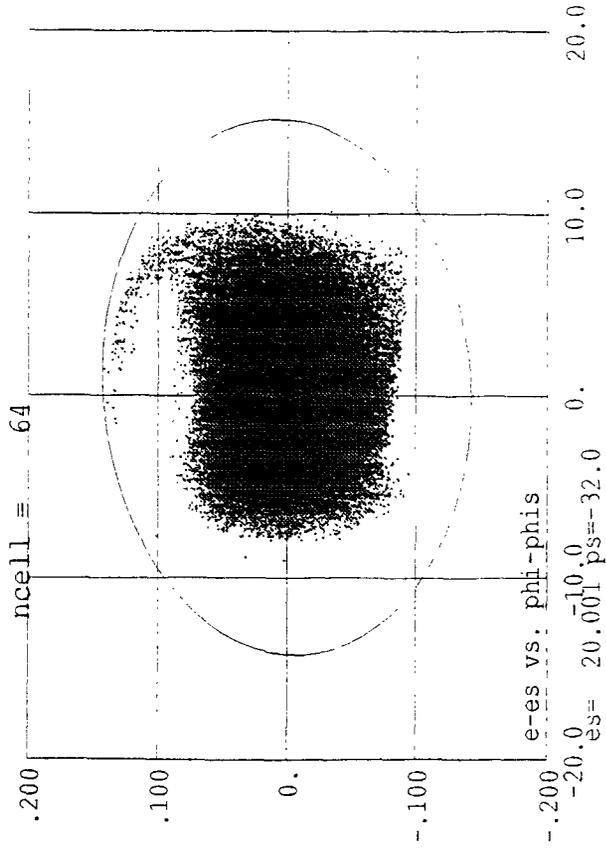
$$E_r = \frac{8\lambda x}{a(a+b)} \left[1 - \frac{x^2(2a+b)}{3a^2(a+b)} - \frac{y^2}{b(a+b)} \right]$$

A = ratio of x^3 term to x term at $x=a$.

B = ratio of xy^2 term to x term at $y=b$.

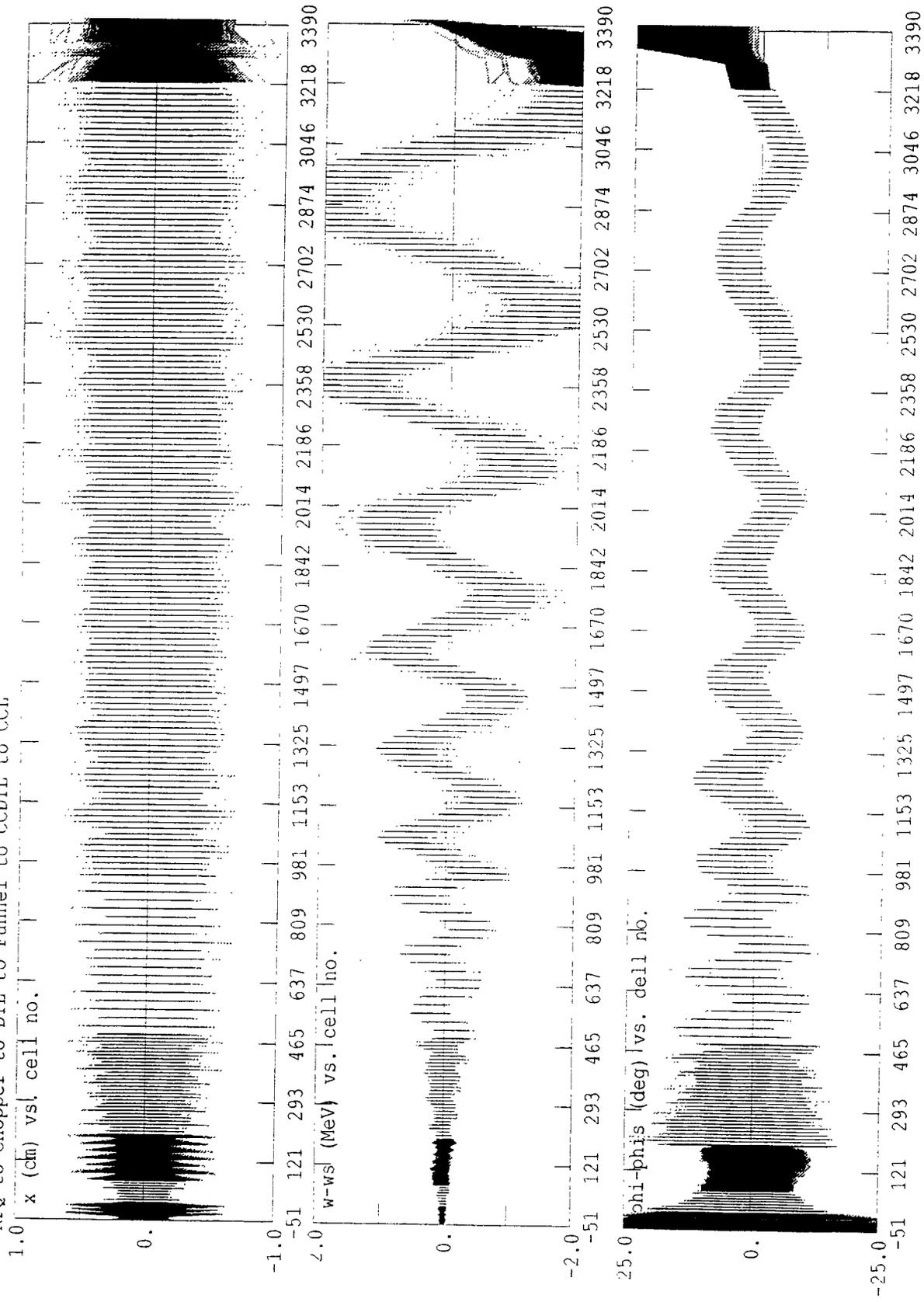
a/b	1	2	0.5	5	0.2
18 A	9	10	8	11	7
18 B	9	6	12	3	15

Linear effect proportional to β_h , non-linear to β_h^2 or $\beta_h\beta_v$.



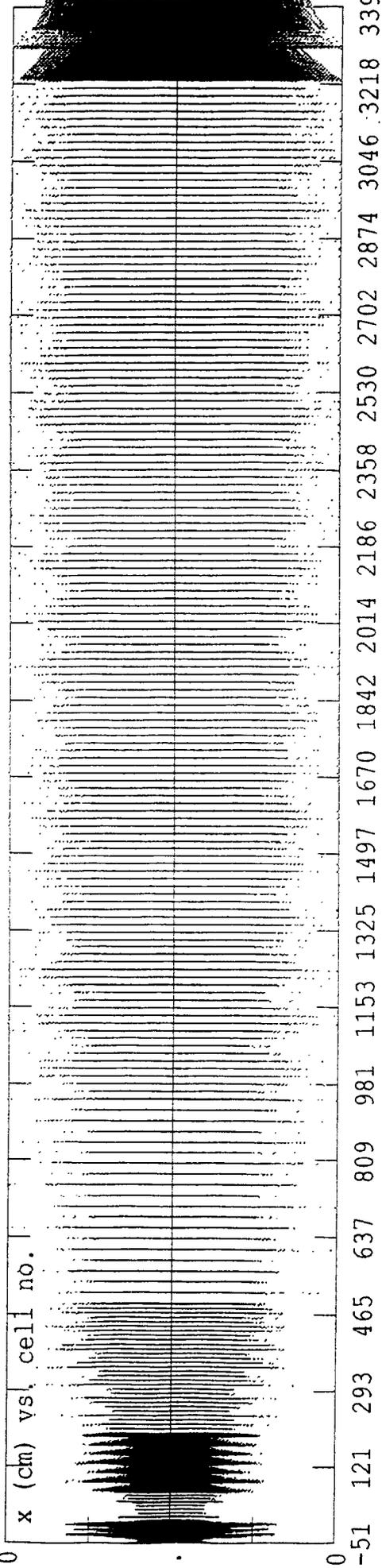
Longitudinal Halo Development in DTL

RFQ to Chopper to DTL to Funnel to CCDTL to CCL

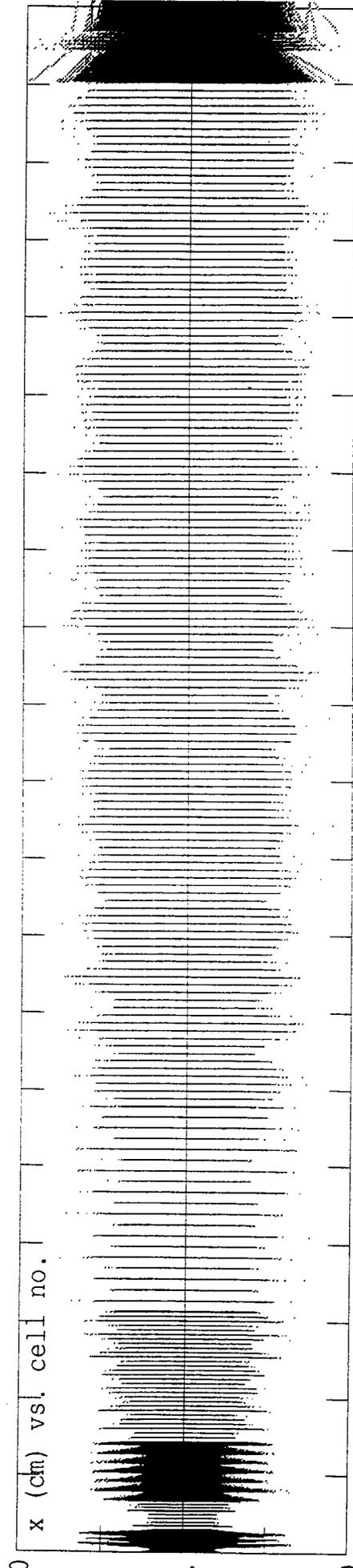


Randomly Distributed RF Field Errors, $\delta E < 1\%$, $\Delta\phi < 1^\circ$

RFQ to Chopper to DTL to Funnel to CCDTL to CCL



a) Case of 10% error in matching quadrupole ahead of CCDTL



b) Case of nominal six parameter matching

Coherent Envelope Mode Extraction

Emittance Growth along Linac (2 x 57 mA)

a) Case of nominal six parameter matching

Longitudinal : rms emittance growth $\sim 10, 12 \%$

maximum halo particle $< 7, 11 \sigma$

Transverse : rms emittance growth $\sim 11.5 \%$

maximum halo particle $< 7 \sigma$

RF errors (0.5%, 0.5°) : additional rms growth $\sim 5 \%$

b) Case of 10 % quadrupole error ahead of CCDTL

Longitudinal : rms emittance growth $\sim 15, 33 \%$

maximum halo particle $< 6.5, 15 \sigma$

Transverse : rms emittance growth $\sim 37, 41 \%$

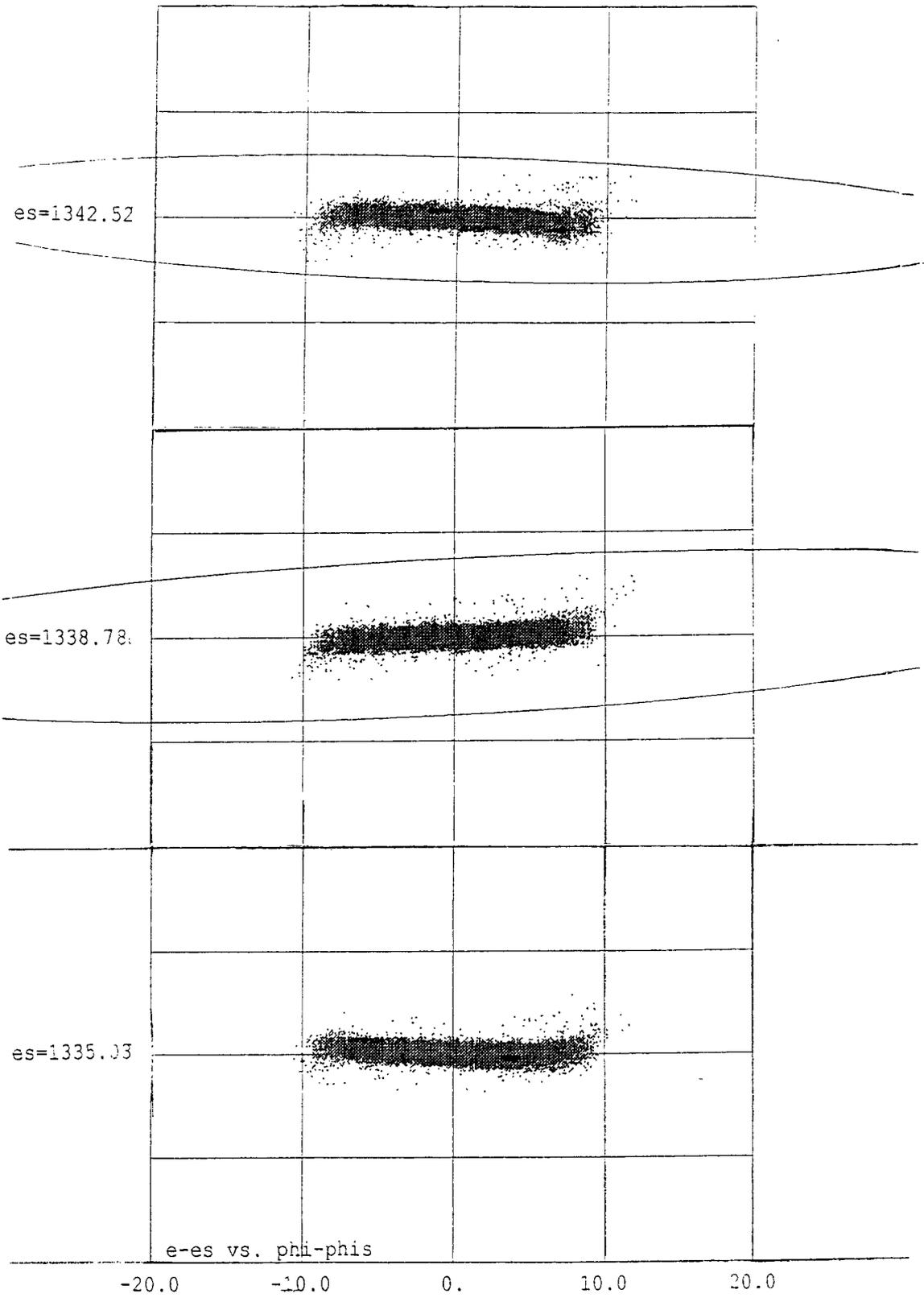
maximum halo particle $< 11, 13 \sigma$

Momentum Error Compensation after Linac

Ramping and debunching cavities at length l after linac

$$V * l = \beta^3 \gamma^3 \left(\frac{E_0}{e} \right) \left(\frac{c}{2\pi f} \right)$$

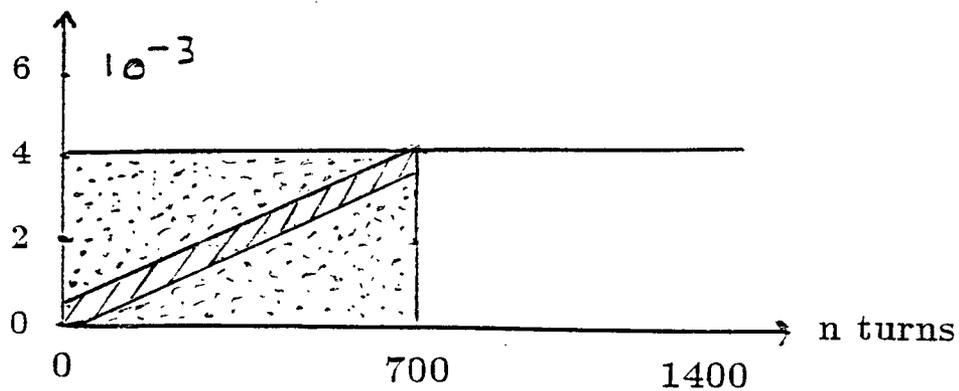
Compensation for ΔE , but $\Delta\phi$ introduces new ΔE error



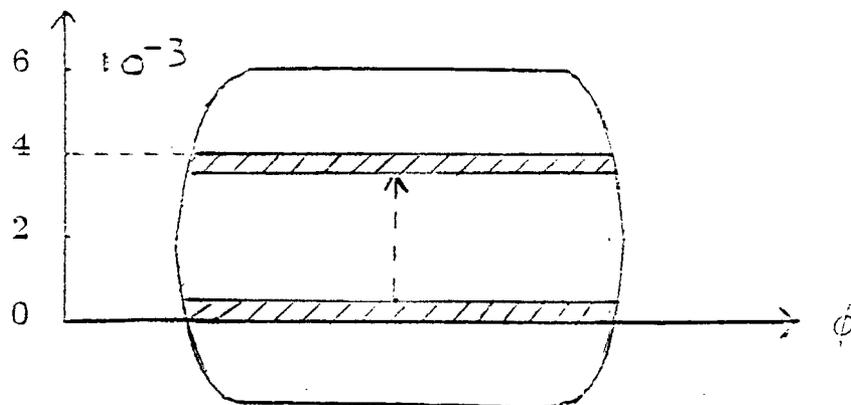
Debunched and Ramped Momentum Range

Momentum Ramping

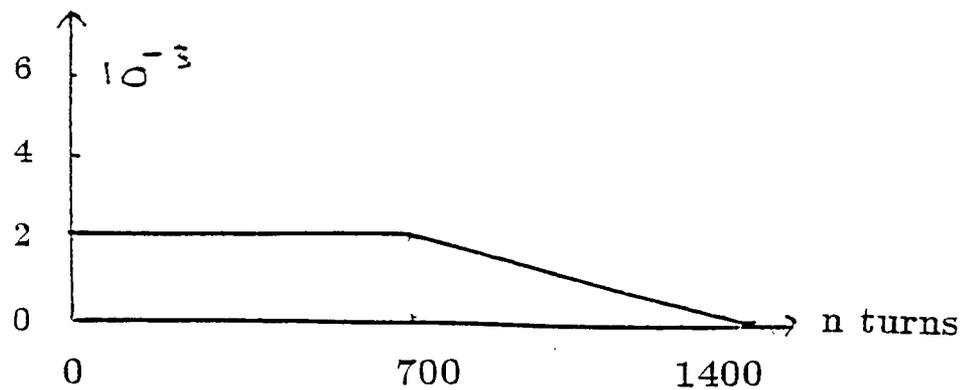
$\Delta p/p$ Injection Ramp



$\Delta p/p$ Injection RF Bucket



$\Delta p/p$ RF Bucket Centre



Instability Topics for ESS Ring

1. Longitudinal space charge - resistive wall instability
2. Coupled control loop - beam loading instability
3. Transverse space charge - resistive wall instability
4. Head-tail instability
5. Electron-proton instability

Space charge impedances are large

Some reduction by smooth profiling of walls

Practical $\Delta p/p$ values give stability for 1, not for 3

Feed-forward allows stability for 2

Design for enhanced growth time for 3

Higher mode, head-tail modes only for 4, at natural ξ

Consider stabilization for 3 and 5

RF System Parameters for Longitudinal Stability

Assume H-P elliptical 2-D longitudinal distribution

$$V = gNeh^2 / (2\epsilon_0 R \gamma^2 F \eta_{sc}) \quad ; \quad \eta_{sc} < 0.4 \text{ for stability}$$

Single harmonic $F_1 = 2(\sin\phi_2 - \phi_2 \cos\phi_2)$

Dual harmonic ($\delta=0.5$) $F_2 = F_1 - \frac{\delta}{4}F_1 (2 \phi_2)$

Barrier bucket ($\mp\phi_3=0.55\pi$) $F_3 = \phi_2^2 - \phi_3^2$

Bunch extremities $\phi_2 = -\phi_1 = 0.691 \pi$

Form factors $F_1 = 4.1 \quad F_2 = 3.94 \quad F_3 = 1.727$

Bunching factors $B_1 = 0.417 \quad B_2 = 0.512 \quad B_3 = 0.621$

RF Voltages for stability with $\eta_{sc} = 0.3$

R(m)	S.H.	D.H.	B.B.	
26.0	19.8	20.6	± 47.0	kV
39.0	13.2	13.7	± 31.3	kV

Dual harmonic system selected for ESS

Profiling of Vacuum Chamber Wall

Smooth contouring for fixed ratio a/b of beam-wall radii

Advantages :

Reduced g value and longitudinal space charge impedance

Reduced voltage for rf system

Reduced beam potential for trapping of electrons

Reduced value for transverse space charge impedance

Reduced external tune spread for transverse stability

Disadvantages :

More complex vacuum chamber, including shielding of bellows

Enhanced resistive wall impedance (b^{-3} dependence)

Recommend partial profiling with shielding of bellows

Transverse Coherent Instabilities

Space charge impedance is above instability threshold levels

$$\frac{RZ_0}{\beta^2\gamma^2} \left(\frac{1}{a^2} - \frac{1}{b^2} \right) |j| > \frac{\pi Q E_0 \beta \gamma}{eIR} \left| (\xi Q - \eta(n - Q)) \frac{\Delta p}{p} \right|$$

for many coasting beam ($n < 160$) modes at chosen $\Delta p/p$ ($\pm 6 \cdot 10^{-3}$)

Concern only for growth times \ll synchrotron period

Approximate growth time for no Landau Damping

$$\tau = Qe\gamma Z_0 / (Ir_p R_\perp)$$

e.g. $\tau \sim 1.0 \text{ ms}$ for $R_\perp = 5 \text{ k}\Omega \text{ m}^{-1}$

Care needed, therefore, with the designs of :

Vacuum chamber (smooth, profiled, Cu or Al inner surface, nitrided)

Bellows sections (all shielded)

Fast extraction kickers (central ground plane, low R_\perp)

Monitors, collimators and cavities (low R_\perp)

Possible Stabilising Mechanisms for Transverse Instabilities

1. Partial stabilisation at natural values of chromaticity, ξ
 - a. tune spreads $\xi Q \Delta p/p$ (fast instabilities)
 - b. some development of head-tail chromatic phase shifts

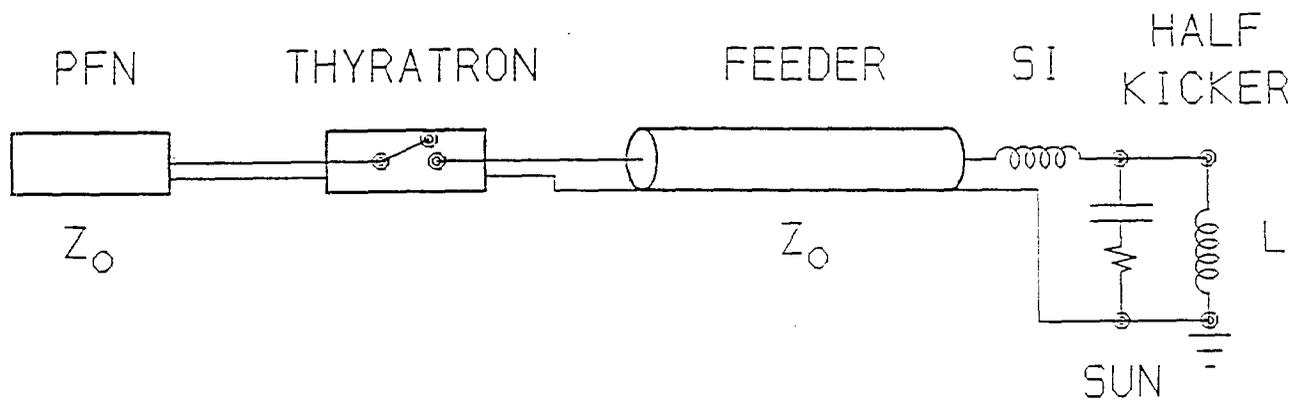
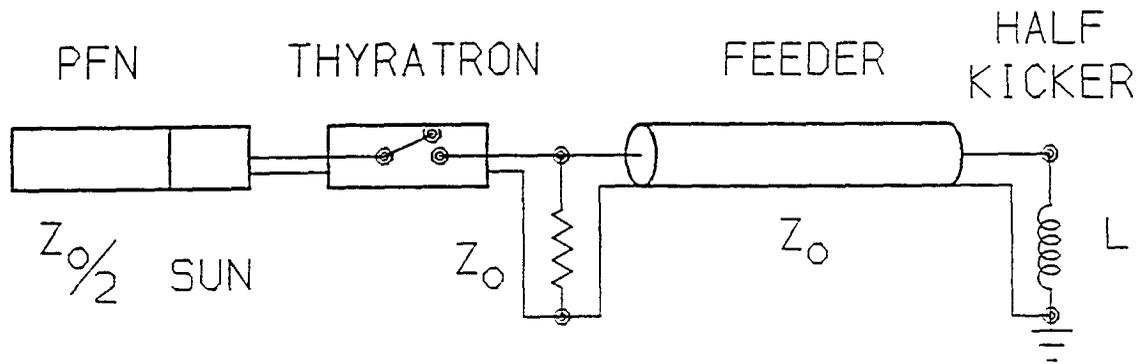
There is insufficient time for significant head-tail motion

Only higher order head-tail modes are possible ($m > 25$)

2. Additional Q-spreads from octupole magnet families (0.15)
3. Low delay, fast, coherent feedback systems
4. Fast variation of betatron tunes
(fast trim quadrupoles and/or rf steering)

Space available in lattice for all options

EXTRACTION PULSERS



- PFN PULSE FORMING NETWORK
- SUN SPEED UP NETWORK
- SI SATURATING FERRITE INDUCTOR
- Z₀ 8.333 Ω

R_{\perp} not measured. ISIS experience suggests $R_{\perp} \ll 5 \text{ k}\Omega\text{m}^{-1}$

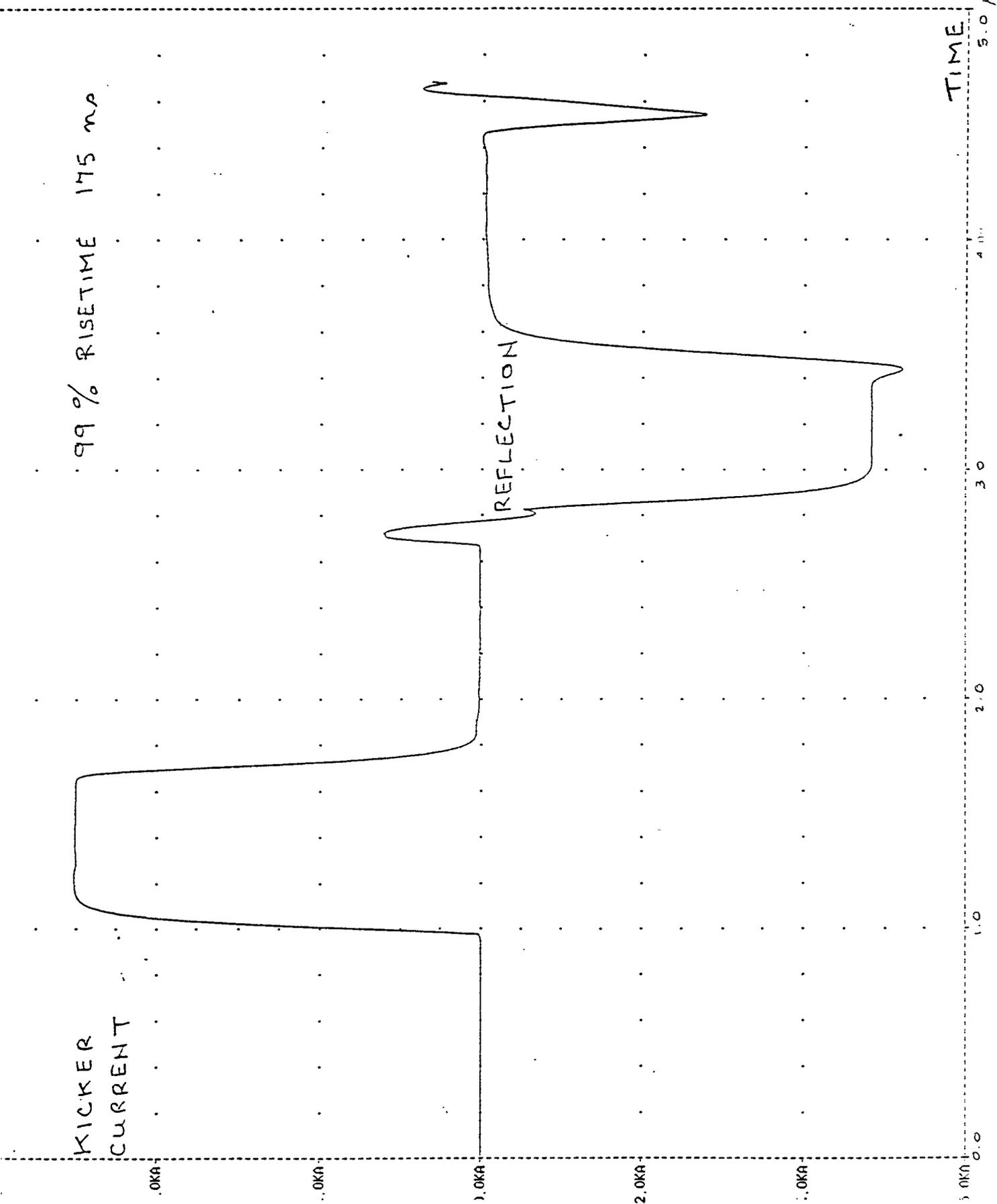
KICKER
CURRENT

99% RISE TIME 175 ns

REFLECTION

TIME

5.0 μ s



Electron-Proton Instabilities

Bunched beam e-p more complex than coasting beam e-p

Electrons trapped in st. sections (or quads?) ; $\geq \frac{1}{4}$ % protons in 'gap'

Trapped electrons must have continually changing osc frequency $Q_c \omega$

Q_c max when peak of bunch passes, Q_c min when 'gap' passes

Longitudinal space charge forces cause drift of electrons in st sections

Trapped e and p attract, force on protons \propto 'earlier' displacement

Antidamping force on coherent transverse proton motion

High values of Q_c , so a range of high n values for (n-Q) proton modes

Motion unstable for values of $n \leq 160$

Instability grows from noise; largest noise from linac bunch residue

Precautions against Electron-Proton Instability

Profile vacuum wall to lower potentials for trapping of electrons
and to lower transverse space charge impedance

Provide shielding for bellows sections

Choose ring rev freq to minimise residue of linac bunch structure

Choose high linac freq (560 MHz) for a stable (n-Q) mode region
(note PSR does not satisfy this condition with $n \sim 70$ at 200 MHz)

Design linac chopper and ring rf for acceptable no. of 'gap' protons

Consider mechanisms for clearing 'gap' protons

Clearing electrodes appear impractical for long straight sections

Design for lower beam densities ($N/(\bar{B}R\varepsilon_t)$) than in PSR

Consider same stabilisation methods as for other transverse instabs